APPENDIX B

CHARACTERIZATION OF SWELL BEHAVIOR FROM SOIL SUCTION

B-1. Introduction

Soil suction is a quantity that can be used to characterize the effect of moisture on volume, and it is a measure of the energy or stress that holds the soil water in the pores or a measure of the pulling stress exerted on the pore water by the soil mass. The total soil suction is expressed as a positive quantity and is defined as the sum of matrix τ_m° and osmotic τ_s suctions.

a. Matrix suction. The matrix suction τ_m° is related to the geometrical configuration of the soil and structure, capillary tension in the pore water, and water sorption forces of the clay particles. This suction is also pressure-dependent and assumed to be related to the in situ pore water pressure u_w by

$$\tau_m^\circ = -u_w + \alpha \sigma_m \qquad \text{(B-1)}$$

$$\sigma_m = \frac{1 + 2K_T}{3} \sigma_v \qquad \text{(B-2)}$$

where

τ_m° = matrix soil suction, tons per square foot
α = compressibility factor, dimensionless
σ_m = total mean normal confining pressure, tons per square foot
K_T = ratio of total horizontal to vertical stress in situ
σ_v = total vertical pressure, tons per square foot

The exponent "°" means that the τ_m° is measured without confining pressure except atmospheric pressure. Experimental results show that the in situ matrix suction τ_m is equivalent to $-u_w$ for soils. The compressibility factor is determined by the procedure in paragraph B-3d.

b. Osmotic suction. The osmotic suction τ_s is caused by the concentration of soluble salts in the pore water, and it is pressure-independent. The effect of the osmotic suction on swell is not well known, but an osmotic effect may be observed if the concentration of soluble salts in the pore water differs from that of the externally available water. For example, swell may occur in the specimen if the external water contains less soluble salts than the pore water. The effect of the osmotic suction on swell behavior is assumed small compared with the effect of the matrix suction. The osmotic suction should not significantly affect heave if the salt concentration is not altered.

B-2. Methods of measurement

Two methods are recommended for determining the total soil suction: thermocouple psychrometer and filter paper. The suction range of thermocouple psychrometers usually is from 1 to 80 tons per square foot while the range of filter paper is from 0.1 to more than 1,000 tons per square foot. Two to seven days are required to reach moisture equilibrium for thermocouple psychrometer, while 7 days are required for filter paper. The thermocouple psychrometer method is simple and can be more accurate than filter paper after the equipment has been calibrated and the operating procedure established. The principal disadvantage is that the suction range is much more limited than the filter paper method, The filter paper method is technically less complicated than the thermocouple psychrometer method; however, the weighing procedure required for filter paper is critical and vulnerable to large error.

a. Calibration. The total soil suction is given on the basis of thermodynamics by the equation

$$\tau^\circ = -\frac{RT}{v_w} \ln \frac{p}{p_o} \qquad \text{(B-3)}$$

where

τ° = total suction free of external pressure except atmospheric pressure, tons per square foot
R = universal gas constant, 86.81 cubic centimetres-tons per square foot/mole-Kelvin
T = absolute temperature, Kelvin
v_w = volume of a mole of liquid water, 18.02 cubic centimetres/mole
p/p_o = relative humidity
p = pressure of water vapor, tons per square foot
p_o = pressure of saturated water vapor, tons per square foot

Equation (B-3) shows that the soil suction is related to the relative humidity in the soil. Both thermocouple psychrometer and filter paper techniques require calibration curves to evaluate the soil relative humidity from which the soil suction may be calculated using equation (B-3). Calibration is usually performed with salt solutions of various known molality (moles of salt per 1,000 grams of water) that produce a given relative humidity. Table B-1 shows the modalities re-

Table B-1. Calibration Salt Solutions

Measured temperature t, °C	Suction, tsf for cited molality of sodium chloride solution 0.053	0.100	0.157	0.273	0.411	0.550	1.000
15	3.05	4.67	7.27	12.56	18.88	25.29	46,55
20	3.10	4.74	7.39	12.75	19.22	25.76	47.50
25	3.15	4.82	7.52	13.01	19.55	26.23	48.44
30	3.22	4.91	7.64	13.22	19.90	26.71	49.37

quired for sodium chloride salt solutions to provide the soil suctions given as a function of temperature.

b. *Thermocouple psychrometer technique.* The thermocouple psychrometer measures relative humidity in soil by a technique called Peltier cooling. By causing a current to flow through a single thermocouple junction in the proper direction, that particular junction will cool, then water will condense on it when the dew-point temperature is reached. Condensation of this water inhibits further cooling of the junction. Evaporation of condensed water from the junction after the cooling current is removed tends to maintain a difference in temperature between the thermocouple and the reference junctions. The microvoltage developed between the thermocouple and the reference junctions is measured by the proper readout equipment and related to the soil suction by a calibration curve.

(1) *Apparatus.* Laboratory measurements to evaluate total soil suction may be made with the apparatus illustrated in figure B-1. The monitoring system includes a cooling circuit with the capability of immediate switching to the voltage readout circuit on termination of the current (fig. B-2). The microvoltmeter (item 1, fig. B-2) should have a maximum range of at least 30 microvolt and allow readings to within 0.01 microvolt. The 12-position rotary selector switch (item 2) allows up to 12 simultaneous psychrometer connections. The 0-25 millimeter (item 3), two 1.5-volt dry cell batteries (item 4), and the variable potentiometer (item 5) form the cooling circuit, Equipment is available commercially to perform these measurements of soil suction.

(2) *Procedure.*

(a) Thermocouple psychrometer are inserted into 1-pint-capacity metal containers with the soil specimens, and the assembly is sealed with No. 13-1/2 rubber stoppers. The assembly is inserted into a 1- by 1- by 1.25-foot chest capable of holding six l-pint containers and insulated with 1.5 inches of foamed polystyrene, Cables from the psychrometer are passed through a 0.5-inch-diameter hole centered in the chest cover, The insides of the metal containers are coated with melted wax to inhibit corrosion of the containers.

(b) The apparatus is left alone until equilibrium is attained. Temperature equilibrium is attained within a few hours after placing the chest cover. Time to reach equilibrium of the relative humidity in the air measured by the psychrometer and the relative humidity in the soil specimen depends on the volume and initial relative humidity in the container. Equilibrium time may require up to 7 days, but may be reduced to 2 or 3 days by repeated testing of soils with similar suctions.

(c) After equilibrium is attained, the microvoltmeter is set on the 10- or 30-microvolt range and zeroed by using a zeroing suppression or offset control. The cooling current of approximately 8 millimeters is applied for 15 seconds and then switched to the microvoltmeter circuit using the switch of item 6 in figure B-2, The maximum reading on the microvoltmeter is recorded. The cooling currents and times should be identical to those used to determine the calibration curves.

(d) The readings can be taken at room temperature, preferably from 20 to 25 degrees Centigrade, and corrected to a temperature of 25 degrees Centigrade by the equation

$$E_{25} = \frac{E_t}{0.325 + 0.027_t} \qquad \text{(B-4)}$$

where

E_{25}= microvolt at 25 degrees Centigrade

E_t= microvolt at t degrees Centigrade

Placement of the apparatus in a constant temperature room will increase the accuracy of the readings.

(3) *Calibration,* The psychrometer are calibrated by placing approximately 50 millilitres of the salt solutions of known molality (table B-1) in the metal containers and following the procedure in b(2) above to determine the microvolt output. Equilibration time may be reduced to 2 or 3 days by surrounding the psychrometer with filter paper soaked with solution. The suctions given for the known modalities are plotted versus the microvolt output for a temperature of 25 degrees Centigrade. The calibration curves of 12 commercial psychrometer using the equipment of figure B-1 were within 5 percent and could be expressed by the equation

$$\tau_0 = 2.65E_{25} - 1.6 \qquad \text{(B-5)}$$

where $\tau°$ is the total soil suction in tons per square foot. The calibration curves using other equipment may be somewhat different.

c. *Filter paper technique.* This method involves enclosing filter paper with a soil specimen in an airtight container until complete moisture equilibrium is

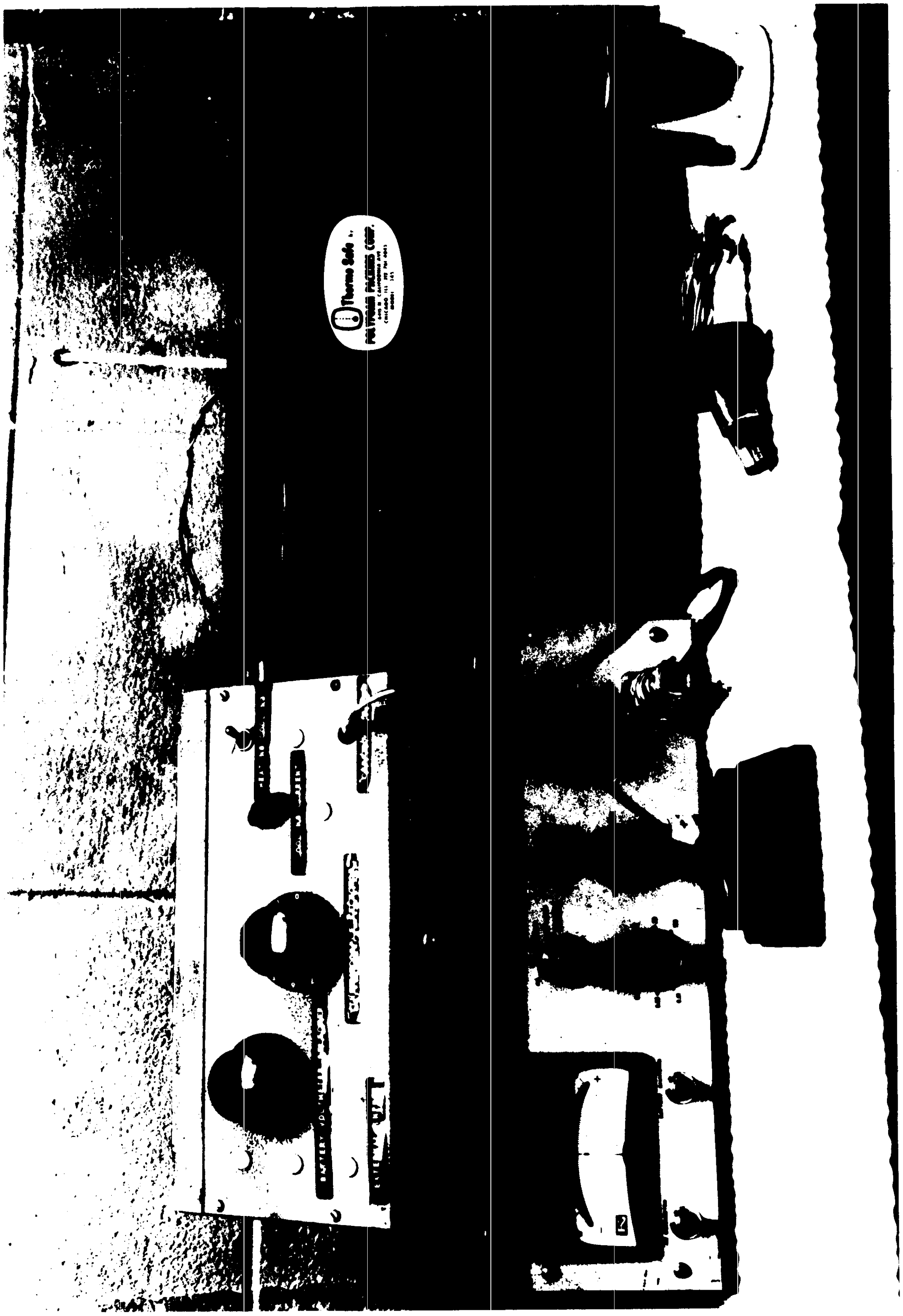

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Figure B-1. Thermocouple psychrometer monitoring apparatus.

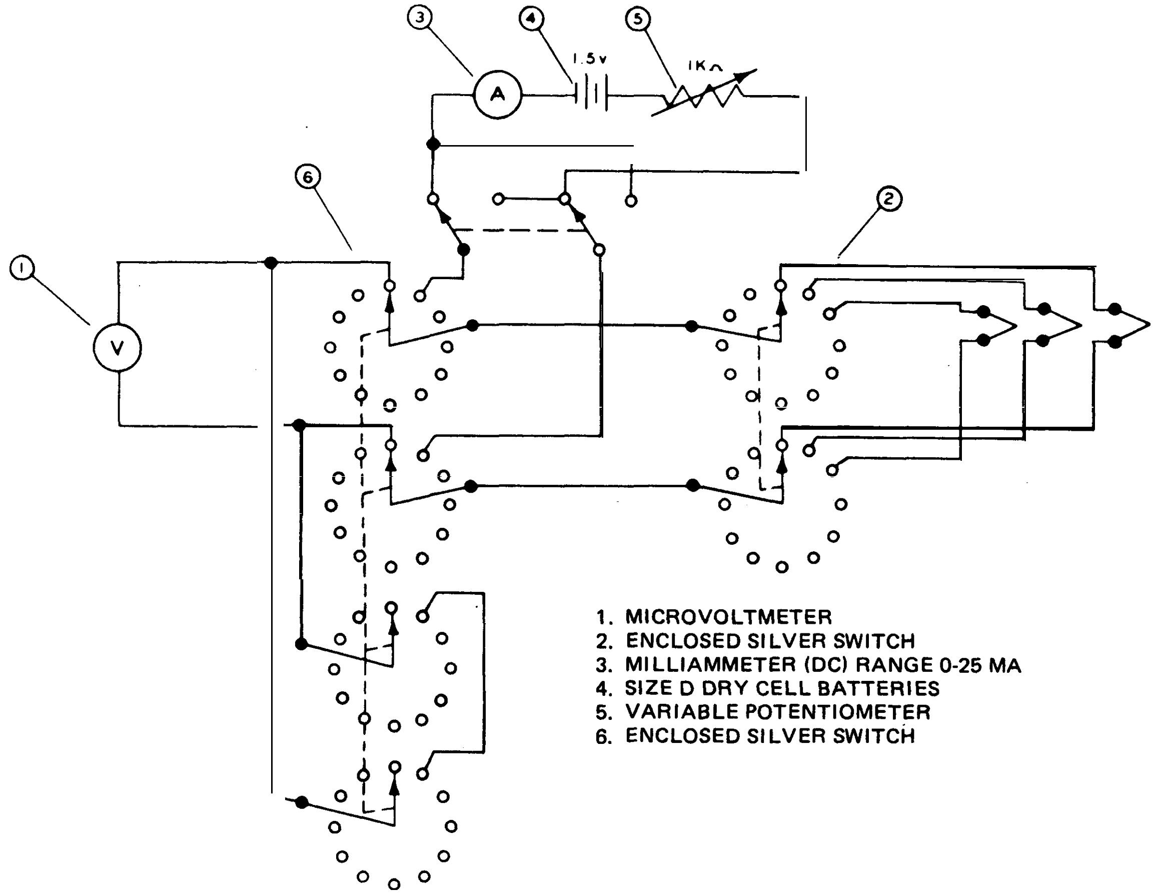

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Figure B-2. Electrical circuit for the thermocouple psychrometer.

reached. The water content in percent of the dry weight is subsequently determined, and the soil suction is found from a calibration curve.

(1) *Apparatus.* Materials consist of 2-inch-diameter filter paper, 2-inch-diameter tares, and a gravimetric scale accurate to 0.001 g. A filter paper is enclosed in an airtight container with the soil specimen.

(2) *Procedure.*

(a) The filter paper disc is pretreated with 3 percent reagent grade pentachlorophenol in ethanol (to inhibit bacteria and deterioration) and allowed to air dry. Reagent grade pentachlorophenol is required because impurities in the treatment solution influence the calibration curve. Care is required to keep the filter paper from becoming contaminated with soil from the specimen, free water, or other contaminant (e.g., the filter paper should not touch the soil specimen, particularly wetted specimens).

(b) Seven days are required to reach moisture equilibrium in the airtight container. At the end of 7 days, the filter paper is transferred to a 2-inch-cliameter covered tare and weighed immediately on a gravimetric scale accurate to 0.001 g. The number of filter papers and tares weighed at one time should be kept small (nine or less) to minimize error caused by water evaporating from the filter paper.

(c) The tare is opened and placed in an oven for at least 4 hours or overnight at a temperature of 110 ± 5 degrees Centigrade. The ovendry weight of the filter paper is then determined, and the water content as a percent of the dry weight is compared with a calibration curve to determine the soil suction.

(3) *Calibration.* The ovendry water content of the filter paper is dependent on the time lapse following removal from the drying oven before weighing.

(a) The calibration curves shown in figure B-3 were determined for various elapsed times following removal from the oven. The calibrations are given for Fisherbrand filter paper, Catalog Number 9-790A, enclosed with salt solutions of various molality for 7 days. Calibration curve No. 1 resulted from weighing the filter paper 5 seconds following removal from the oven. Time lapses of 15 minutes and 4 hours lead to a similar calibration curve (No. 3) of significantly smaller water contents than the 5-second curve for identical suctions. Calibration curve No. 2 was determined

by removing 12 specimens from the oven, waiting 30 seconds to cool, then weighing as soon as possible and within 15 minutes.

(b) Calibration curves based on the method used to determine curve No, 3 with a waiting time between 15 and 30 minutes are recommended if the suctions of

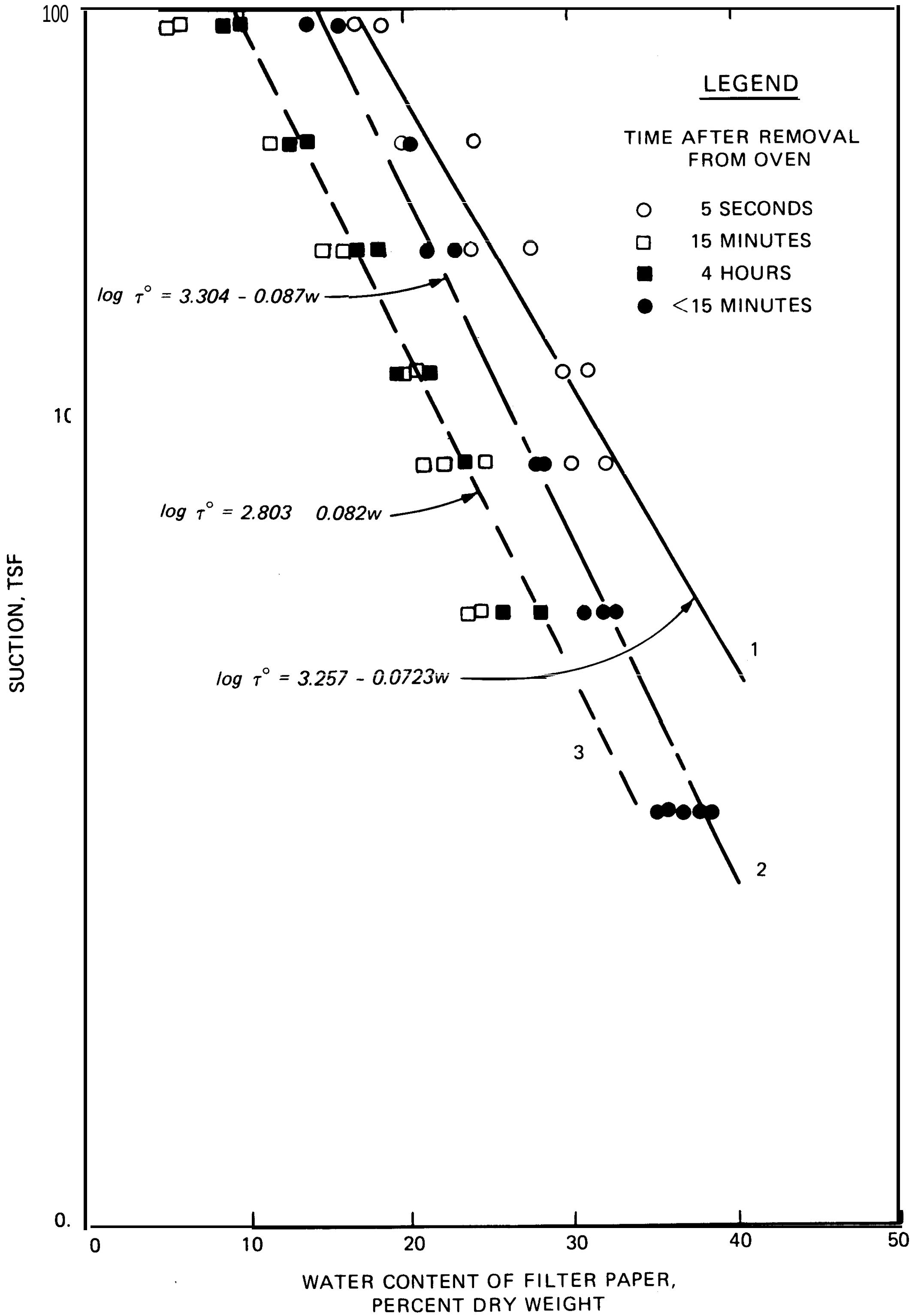

Figure B-3. Calibration of filter paper.

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large numbers of specimens are to be evaluated. However, the accuracy will be less than if curve No. 1 and its procedure are used because curve No. 3 can be influenced by changes in the relative humidity of the testing room. The gravimetric scale should be located near the drying oven for the 5-second calibration curve (No. 1) to be practical. Changes in filter paper weights are normally small (e.g., less than 0.1 g) and require accurate calibration of the gravimetric scale and adherence to a single standardized procedure.

B-3. Characterization of swell behavior

The swell behavior of a particular soil may be characterized from the matrix suction-water content relationship and the compressibility factor α to calculate heave by the equation

$$\frac{\Delta H}{H} = \frac{e_1 - e_o}{1 + e_o} = \frac{C_\tau}{1 + e_o} \log \frac{\tau^{\circ}_{mo}}{\tau^{\circ}_{mf}} \quad \text{(B-6)}$$

where

ΔH = potential vertical heave at the bottom of the foundation, feet
H = thickness of the swelling soil
e_1 = final void ratio following swell
e_o = initial void ratio
C_τ = $\alpha G_s/100B$, suction index
α = compressibility factor
G_s = specific gravity
B = slope soil suction parameter
τ°_{mo} = initial matrix suction without surcharge pressure, tons per square foot
τ°_{mf} = final matrix suction without surcharge pressure, tons per square foot

The suction index C_τ is similar to $\gamma_h(1 + e_o)$ where γ_h is the suction compression index of the McKeen-Lytton method in table 4-2. Equation (B-6) is similar to equation (5-2) of paragraph 5-4*a* and equation (5-8) of paragraph 5-4*a* from which the total potential heave is calculated. Equation (B-6) will also lead to the same or similar predictions of heave for identical changes in suction. The suction index, a measure of the swelling capability, is analogous to the swell index c_s of consolidometer swell tests, except that the suction index is evaluated with respect to the change in matrix suction without surcharge pressure rather than the change in effective pressure.

a. Matrix suction and water content relationship. This relationship is evaluated from the total soil suction and water content relationship. The total soil suction as a function of water content is found from multiple 1-inch pieces of the undisturbed sample. The pore water may be evaporated at room temperature, for various periods of time up to about 48 hours, from several undisturbed specimens; various amounts of distilled water may also be added to several other undisturbed specimens of each sample to obtain a multipoint water content distribution. Each specimen may be inserted into a 1-pint metal container with a thermocouple psychrometer or with filter paper to evaluate the total soil suction as previously described. The dry density and void ratio of each undisturbed specimen from which the compressibility factor α is determined may be evaluated by the water displacement method. Using thermocouple psychrometers, collect soil suction data on DA Form 5182-R (Soil Suction, Water Content and Specific Volume). DA Form 5182-R will be reproduced locally on 11- by 8½-inch paper. A copy of DA Form 5182-R for local reproduction purposes can be found at the back of this manual.

(1) The multipoint total soil suction and water content relationship may be plotted as shown in figure B-4 for each undisturbed sample. The open circles in the figure represent natural water content w_o, and the closed circles symbolize water being added to or evaporated from the undisturbed specimens at room temperature. An osmotic suction τ_s is sometimes indicated by a horizontally inclined slope at high water contents, and the magnitude may be estimated by noting the total soil suction at high water contents. Large osmotic suctions appreciably flatten the slope as shown in figure B-4. The matrix suction and water content relationship can be approximated by subtracting the osmotic suction from the total soil suctions and expressing the result as

$$\log \tau^{\circ}_{m} = A - Bw \quad \text{(B-7)}$$

where

τ°_{m} = matrix suction without surcharge pressure, tons per square foot
A = ordinate intercept soil suction parameter, tons per square foot
B = slope soil suction parameter
w = water content, percent dry weight

Information on piezometric pore water pressures is used in approximating the matrix suction and water content relationship in the presence of appreciable osmotic suctions.

(2) The matrix suction and water content relationship of figure B-4 was approximated by noting that the groundwater elevation, at which $u_w = 0$, was 1.5 feet. Hence, the matrix suction at the natural water content of 27 percent was the total mean confining pressure σ_m of approximately 0.1 ton per square foot from equation (B-1). The value σ_m may be estimated from equation (B-2) if K_T can be approximated. The remainder of the curve was approximated by subtracting 26 tons per square foot, which was the total average suction at the natural water content of 27 percent less 0.1 ton per square foot, from the total soil suction observed at smaller water contents. The osmotic suction should be subtracted from the total suction; otherwise heave predictions will be overestimated since the osmotic suction does not appear to cause much heave and

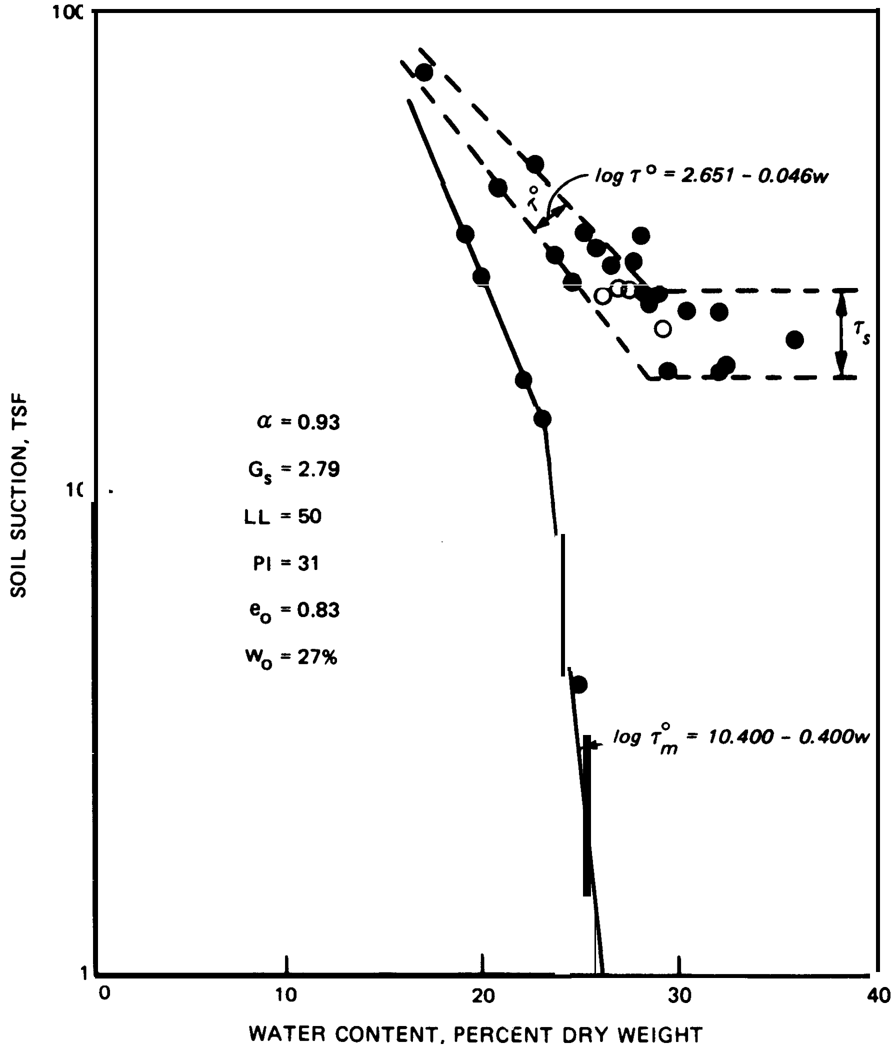

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Figure B-4. Soil suction and water content relationship for Fort Carson overburden at 1 to 3 feet of depth.

if the equilibrium moisture profiles of figure 5-1 (para 5-4b) are used.

b. Initial matrix suction. The initial matrix suction τ&without surcharge pressure may be evaluated using the soil suction test procedure on undisturbed specimens or may be calculated from equation (B-7) and the natural (initial) water content.

c. Final matrix suction. The final matrix suction τ°_{mf} without surcharge pressure may be calculated from the assumption

$$\tau^{\circ}_{mf} = \left(\frac{1 + 2K}{3}\right) \sigma'_v \qquad \text{(B-8)}$$

K = coefficient of effective lateral earth pressure

σ'_v = final vertical effective pressure, tons per square foot or from equation (B-1) setting a = 1 and if K_T can be approximated.

The final vertical effective pressure may be found from

$$\sigma'_v = \sigma_v - u_w \qquad \text{(B-9)}$$

where σ_v is the final total vertical pressure. The pore water pressure u_w (fig. 5-1) is found from equations (5-3), (5-4), or (5-5).

d. Compressibility factor. The compressibility factor *a* is the ratio of the change in volume for a corresponding change in water content, i.e., the slope of the curve γ_w/γ_d plotted as a function of the water content where γ_w is the unit weight of water and γ_d is the dry density. The value of *a* for highly plastic soils is close to 1, and much less than 1 for sandy and low plasticity soils. High compressibility y factors can indicate highly swelling soils; however, soils with all voids filled with water also have a equal to 1.

(1) Figure B-5 illustrates the compressibility factor calculated from laboratory data for a silty clay taken from a field test section near Clinton, Mississippi. Extrapolating the line to zero water content, as shown in the figure, provides an estimate of l/R with

$$R = \frac{W_s}{V_o} \qquad \text{(B-10)}$$

where

R = shrinkage ratio

W_s = mass of a specimen of ovendried soil, grams

V_o = volume of a specimen of ovendried soil, cubic centimetres

(2) The shrinkage limit SL of the clay shown in figure B-5 may be taken as the abrupt change in slope of the curve, which is 23.3 percent. The SL is calculated by the following equation:

$$SL = w - \frac{V - V_o}{W_s} \times 100 \qquad \text{(B-11)}$$

where w is the water content and V is the volume of the wet soil specimen in cubic centimetres. Equation (B-11) assumes that $\alpha = 1$. For soils with α less than 1, the SL varies depending on the initial water content of the specimen. For example, if the initial water content is at the natural water content of 25.7 percent, then equation (B-11) will give

$$SL = 25.7 - (0.658 - 0.588)\,100 = 18.7 \qquad \text{(B-12)}$$

as shown in figure B-5. Other shrinkage limits may be evaluated by drawing straight lines with slope $\alpha = 1$ through other water content points. Soils with the PI less than 40 are more likely to indicate compressibility factors less than 1 than higher plasticity soils. Equation (B-11) is not applicable to soils with α much less than 1.

e. Examples.

(1) The potential heave of the soil characterized by figure B-4 may be calculated from equation (B-6). The final in situ pore water pressure u_w is equal to 0 at the groundwater level of 1.5 feet. If the depth H is 1.5 feet, then $\sigma_v = 0.09$ ton per square foot. From these variables and the parameters in DA Form 5182-R.

$$C_\tau = \frac{\alpha G_s}{100B} = \frac{(0.93)(2.79)}{(100)(0.400)} = 0.065$$

$$\tau^o_{mo} = 10^{10.400-0.400w_o} = 0.398 \text{ ton per square foot}$$

$$\tau^o_{mf} = u_w + \alpha\sigma_v = 0 + 0.93\,(0.09) = 0.084 \text{ ton per square foot}$$

Therefore,

$$\frac{\Delta H}{H} = \frac{C_\tau}{1 + e_o} \log \frac{\tau^o_{mo}}{\tau^o_{mf}}$$

$$= \frac{0.065}{1 + 0.83} \log \frac{0.398}{0.084} = 0.024$$

The potential heave ΔH will be 0.036 foot or 0.4 inch for the 1.5-foot layer of soil overburden. Practically, the computation indicates that ½ inch of heave is expected.

(2) If the osmotic component of suction is not known, then the potential heave may still be roughly approximated by noting that the mean minimum total suction at high water content is 22 tons per square foot in the example of figure B-4. This value may be taken as the final total soil suction τ^o_f. The initial value of total soil suction τ^o_o is found by noting that the mean total soil suction at natural water content is 26 tons per square foot in figure B-4. The slope B of the total soil suction and water content curve is subsequently used to evaluate the suction index C_τ. The potential heave for this case will be

$$CT = \frac{(0.93)\ (2.79)}{(100)\ (0{,}046)} = 0.564$$

$$\frac{\Delta H}{H} = \frac{C_\tau}{1 + e_o} \log \frac{\tau^o_o}{\tau^o_f}$$

$$= \frac{0.564}{1 + 0.83} \log \frac{26}{22} = 0.022$$

The potential heave ΔH will be 0.033 foot or 0.4 inch for the 1.5-foot layer of soil overburden. The disadvantage of this latter approach is that the equilibrium matrix suction or pore water pressure profile is not known, except that the final matrix suction will be small and probably close to the saturated profile (equation (5-3)). The program HEAVE will compute the potential heave for this case as well as those shown in figure 5-1.

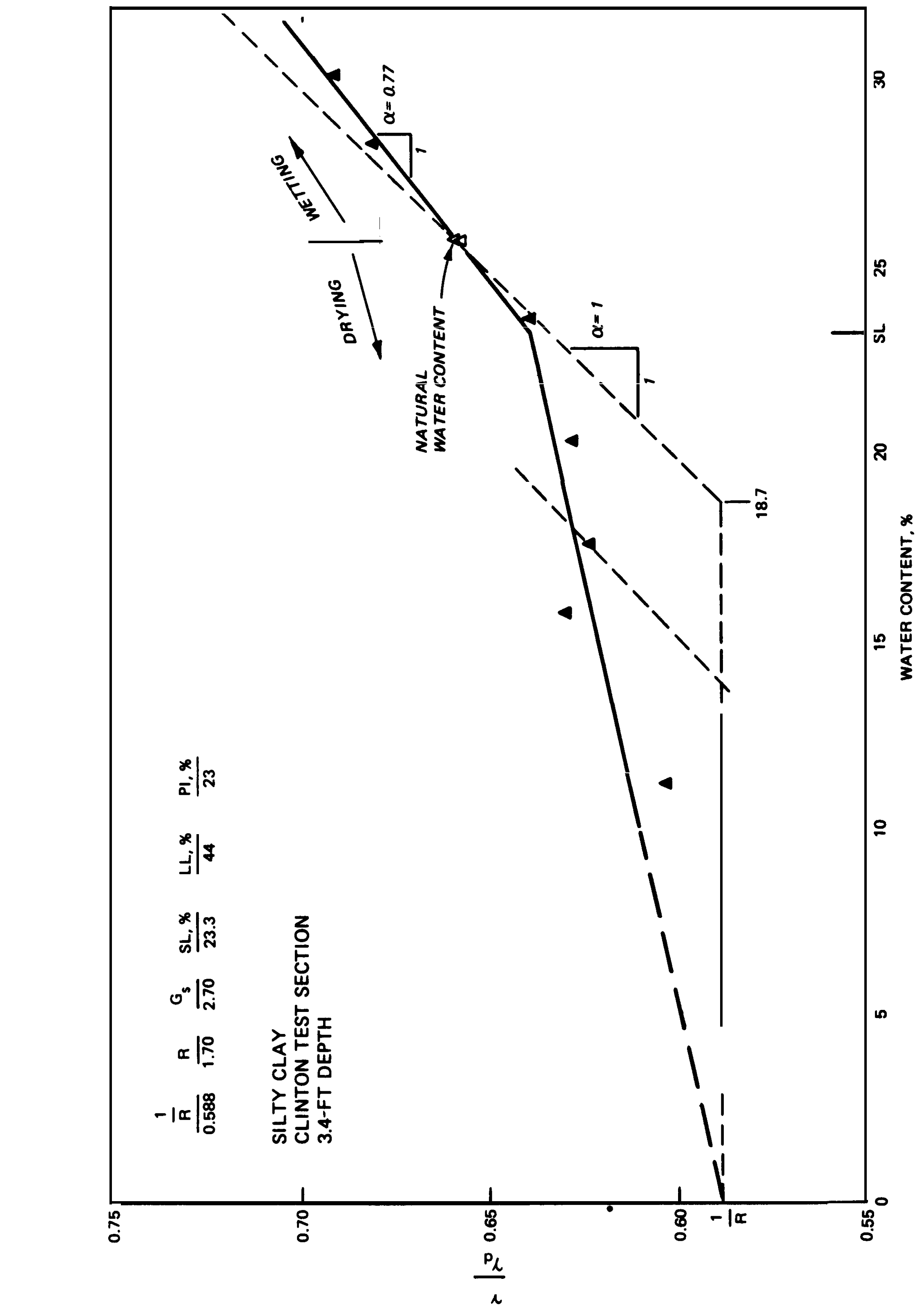

Figure B-5. Illustration of the compressibility factor.